

Settling accretion on to isolated neutron stars from interstellar medium

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ABSTRACT

We apply the model of subsonic settling accretion on to isolated neutron stars accreting from the interstellar medium (AINS). We show that in this regime the expected mean X-ray luminosity from AINS turns out to be 2-3 orders of magnitude as small as the maximum possible Bondi value, i.e. $10^{27} - 10^{28}$ erg s⁻¹. The intrinsically unstable character of settling accretion due to long plasma cooling time leads to regular appearance of X-ray flares with a duration of about one hour and a maximum luminosity of about the Bondi value, $\sim 10^{31}$ erg s⁻¹. This feature can be used to distinguished AINS from other dim X-ray sources. With the sensitivity of the forthcoming all-sky X-ray surveys the expected number of the potentially detectable AINS can be from a few to ten.

Key words: stars: neutron — accretion, accretions discs —

1 INTRODUCTION

Already in the early 1970s it was proposed that old isolated neutron stars (INSs) can reach the evolutionary stage at which their rotation is slow enough to allow accretion from the interstellar medium (ISM) (Shvartsman 1971b; Ostriker et al. 1970). Despite early optimistic estimates (Treves & Colpi 1991), the ROSAT satellite failed to find any object from this class (see a review of results of that time in Treves et al. 2000). This negative result has been thought either to be a consequence of very low accretion luminosities due to large average spatial velocities of NSs (Colpi et al. 1998), or due to a long time of spin evolution required for the NS to start accreting matter, which could be also because of large spatial velocities of INS (Popov et al. 2000). However, it was demonstrated (Boldin & Popov 2010) that INSs with initially large magnetic fields, which are believed not to decay significantly below $\sim 10^{13}$ G, can become accreting isolated neutron stars (AINS), and potentially can be detected by the eROSITA mission (Predehl et al. 2011).

Additional argument against the detectability of AINS by existing X-ray facilities became popular when it was recognized that the Bondi accretion rate \dot{M}_B is only an upper limit for the accretion rate on to a INS moving in ISM. The actual amount of matter that reaches the NS surface and contributes to the potential X-ray luminosity can be much lower than that derived from the Bondi rate. Such a reduc-

tion was found, for example, in numerical MHD simulations of accretion on to a magnetized INS (Toropina et al. 2003).

Steady-state quasi-spherical accretion on to a gravitating center was first considered by Bondi (1952). The exact solution of the hydrodynamical problem was obtained for adiabatic gas motion. Both subsonic and supersonic accretion regimes were found. Recently, the quasi-spherical accretion on to magnetized slowly rotating NS with account for cooling and heating of the accreting gas was revisited in a series of papers by Shakura et al. (Shakura et al. 2012, 2013, 2014, see Shakura et al. 2015 for the latest review). It was recognized that at low X-ray luminosities the captured matter, heated in the bow-shock, has no time to cool down and remains hot, which prevents it from entering the NS magnetosphere via Rayleigh-Taylor (RT) instability (Elsner & Lamb 1977). Therefore, a hot and possibly convective quasi-spherical shell is formed around the magnetosphere. The accretion rate through the shell at the stage of this settling subsonic accretion is determined by the ability of the plasma to enter the magnetosphere, which is controlled by the plasma cooling time: $\dot{M}_x \simeq (t_{\text{ff}}/t_{\text{cool}})^{1/3} \dot{M}_B$, where t_{ff} is the characteristic free-fall time and t_{cool} is the plasma cooling time. The latter can be due to Compton processes (if the photon field is sufficiently dense, e.g. at a high X-ray luminosity), or radiative processes, etc. The regime of such a subsonic settling accretion can be realized in sources with X-ray luminosities below $L_x \lesssim 4 \times 10^{36}$ erg s⁻¹. At higher luminosities, the matter cools down on a time scale

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shorter than the free-fall time and accretes supersonically towards the NS magnetosphere, and $\dot{M}_x = \dot{M}_B$.

Apparently, conditions for settling accretion are fulfilled for INSs accreting from ISM, and in this note we discuss the applicability of the settling accretion regime to this class of NSs. We show that the X-ray luminosity of such AINS is substantially reduced due to the lack of significant cooling plasma mechanisms. When accretion from ISM starts, an AINS rapidly spins down due to the angular momentum transfer by viscous stresses in the surrounding shell, and therefore most of the AINS are expected to be relatively dim long-period X-ray sources.

2 SETTLING ACCRETION ON TO AINS

We start with basic considerations related to accretion on to INSs from ISM.

Despite low densities and high temperatures of the gas falling to the NS from ISM, accretion can be treated hydrodynamically (Shvartsman 1971a). Indeed, in the presence of magnetic field, the mean-free path of a proton is determined by its Larmor radius: $r_g = m_p v_T c / (eB)$. Here m_p and e are the mass and the charge of a proton, v_T is the component of the proton thermal velocity perpendicular to the field line, c is the speed of light, B is the magnetic field. The relevant dimensionless number is the Knudsen number, which in our case can be determined as $\text{Kn} = r_g / R_A$, where R_A is the magnetosphere (Alfvén) radius. As the thermal velocity of particles during accretion on to an INS cannot exceed the free-fall velocity, $v_T \leq v_{\text{ff}}(R_A)$, the Knudsen number can be re-written as the ratio of the Keplerian frequency at R_A to the Larmor frequency: $\text{Kn} \lesssim \omega_K / \omega_L$. Numerically, $\omega_K = \sqrt{GM/R_A^3} \sim 10^{-2} \text{ rad s}^{-1} (R_A/10^{10} \text{ cm})^{-3/2}$ and $\omega_L = m_p c / (eB) \sim 10^2 \text{ rad s}^{-1} B_{\mu\text{G}}^{-1}$ (here $B_{\mu\text{G}}$ is the magnetic field in microGauss). Therefore, for realistic conditions in an accretion flow on to a INS we have $\text{Kn} \ll 1$, i.e. the mean-free path is much smaller than the scale of the problem, and the hydrodynamic treatment of accretion is justified.

According to the classical Bondi-Hoyle-Littleton accretion picture, matter is gravitationally captured by a NS inside the Bondi radius:

$$R_B = 2GM/v^2 \approx 4 \times 10^{12} (M/M_\odot) v_7^{-2} \text{ cm}. \quad (1)$$

Here M is the NS mass, $v_7 = v/10^7 \text{ cm s}^{-1}$ is the spatial velocity of the NS in ISM (below we assume the NS velocity to be larger than the sound velocity in ISM, $v > c_s \sim 10 \text{ km s}^{-1}$, and so the latter can be neglected).

The corresponding Bondi-Hoyle-Littleton accretion rate is given by the standard relation:

$$\dot{M}_B = \rho_\infty v (\pi R_G^2) \sim 1.9 \times 10^9 n v_7^{-3} \text{ g s}^{-1}, \quad (2)$$

where ρ_∞ is ISM matter density (typically $\rho_\infty = 10^{-24} \text{ g cm}^{-3}$, roughly corresponding to the particle number density $n \sim 1 \text{ cm}^{-3}$).

In the settling accretion regime, the mass accretion rate on to the NS surface \dot{M}_x is controlled by the plasma cooling near the magnetospheric boundary:

$$\dot{M}_x \simeq \dot{M}_B (t_{\text{ff}}/t_{\text{cool}})^{1/3}. \quad (3)$$

Here the free-fall time t_{ff} is defined as $t_{\text{ff}} = R^{3/2}/\sqrt{GM}$.

The plasma cooling time inside the boundary layer above the NS magnetosphere, t_{cool} , can be determined by different processes: Compton cooling, radiative losses, cyclotron emission, etc. In the case of AINS we expect very low accretion rates and X-ray luminosities. Formally, in spherically symmetric photon fields the Compton cooling time becomes longer than the radiative cooling time only at very low X-ray luminosities, but as was explained in Shakura et al. (2013), already at X-ray luminosities $\sim 10^{35} \text{ erg s}^{-1}$ and below, the X-rays generated near the NS surface should be narrowly beamed towards the magnetospheric cusp, which is more stable against the RT instability than the magnetospheric equator. Thus, the accretion rate will be determined by less efficient radiative plasma cooling near the magnetospheric equator.

Near the magnetosphere, the cyclotron cooling can operate. However, estimates show (see below) that the cyclotron emission can also be neglected. At virial temperatures near the NS magnetospheric boundary $T \sim 10^7 [\text{K}] (R_A/10^{10} [\text{cm}])^{-1}$ the plasma cooling is entirely due to free-free emission. In this case the cooling time is:

$$t_{\text{cool}} = 3 \times 10^8 \left(\frac{R_A}{10^{10} \text{ cm}} \right) \times \left(\frac{L_x}{10^{30} \text{ erg s}^{-1}} \right)^{-1} \frac{f(u)}{0.01} (1+X)^{-1} \text{ s}. \quad (4)$$

Here R_A is the Alfvén radius, L_x is the X-ray luminosity, $f(u)$ is the dimensionless factor determining the radial settling velocity through the shell, u_r , in units of the free-fall velocity, $f(u) = u_r/u_{\text{ff}} < 1$ (essentially, the ratio $(t_{\text{ff}}/t_{\text{cool}})^{1/3}$). By X we denote possible additional contributions normalized to the bremsstrahlung losses.

The gas accreting from ISM necessarily brings chaotic magnetic fields, therefore the cyclotron emission can contribute to the plasma cooling. The cyclotron losses can be estimated using equations from Langer et al. (1982). It is easy to show that for reasonable assumptions about NS and ISM characteristics, the cyclotron losses are always significantly smaller than bremsstrahlung. Only in the case of INSs moving with very slow velocities ($v \lesssim 10^6 \text{ cm s}^{-1}$), when $R_B/R_A \approx 10^4$, the value of X can formally reach unity for the fiducial ISM number density $n \sim 1 \text{ cm}^{-3}$ and the magnetic field in ISM $\sim \text{few } \mu\text{G}$.¹ Actually, large values of magnetic fields in the accreting plasma due to the magnetic flux conservation in the accreting flow cannot be reached. In the first place, in the settling envelope the magnetic field growth is expected to be slower than r^{-2} . In addition, values $B > 1 \text{ G}$ at the bottom of the envelope cannot be reached as the magnetic field energy cannot be larger than the equipartition value ($B^2 \sim v_{\text{ff}} M_B / R_A^2$). Therefore, below we will ignore any losses except free-free emission ($X \ll 1$).

In the settling accretion model with radiative plasma cooling (Shakura et al. 2013) the Alfvén radius is:

$$R_A \approx 2.2 \times 10^{10} L_{30}^{-2/9} \mu_{30}^{16/27} \text{ cm}. \quad (5)$$

¹ Note that the reduction of R_A in INS with magnetic fields smaller than the standard 10^{12} G does not help much, since INSs with small μ can hardly spin-down during the lifetime of the Galaxy to start accreting from ISM (see Popov et al. 2000; Boldin & Popov 2010).

Here $L_{30} = L_x/10^{30} \text{ erg s}^{-1}$. The value of the dimensionless parameter $f(u)$ is:

$$f(u, \dot{M}_x)_{\text{rad}} \simeq 0.005 \left(\dot{M}_x/10^{10} \text{ g s}^{-1} \right)^{2/9} \mu_{30}^{2/27} (1+X)^{1/3}. \quad (6)$$

In this expression $\mu = B_0 R_{\text{NS}}^3/2$ is the NS dipole magnetic moment in units of 10^{30} G cm^3 , B_0 is the NS polar magnetic field. Thus, the expected accretion rate on to AINS is $\dot{M}_x = f(u, \dot{M}_x)_{\text{rad}} \dot{M}_B$. Substituting here for $f(u)_{\text{rad}}$ from Eq.(6) and solving for \dot{M}_x , we find:

$$\frac{\dot{M}_x}{10^{10} \text{ g s}^{-1}} \simeq 0.001 \mu_{30}^{2/21} (1+X)^{3/7} \left(\frac{\dot{M}_B}{10^{10} \text{ g s}^{-1}} \right)^{9/7}. \quad (7)$$

This formula implies that the actual average accreting luminosity should be much smaller than the potential (Bondi) accretion luminosity of an AINS.

At this point a note on the character of accretion is in order. At low accretion rates, when the Compton cooling is ineffective, the average velocity of the magnetosphere plasma entry due to RT instability mediated by radiative cooling (see $f(u)_{\text{rad}}$ above) is about one percent of the free-fall velocity. It is still much larger than the plasma entry velocities due to other possible mechanisms (diffusion, cusp instability and chaotic magnetic reconnection, see e.g. Elsner & Lamb 1984). Since the radiative cooling time in this case is $1/f(u)_{\text{rad}}^3 \sim 10^6$ times as long as the free-fall time $t_{\text{ff}}(R_A) \sim 100 \text{ s}$, the accretion should apparently proceed as a series of bursts with the duration determined by the RT time instability, $t_{\text{inst}} \sim t_{\text{ff}}(R_A)/f(u)_{\text{rad}} \sim 10^4 \text{ s}$ (see discussion in Shakura et al. 2013). That is, the system should “wait” for a fresh portion of hot accreting plasma to cool down enough for RT instability to fully develop. The peak luminosity during the outbursts can be as high as during the Bondi accretion, i.e. about $0.1 \dot{M}_B c^2 \sim 10^{31} \text{ erg s}^{-1}$ for typical parameters.

3 SPIN-DOWN OF AINS

Now let us consider the spin-down of AINS in the settling accretion regime. Spin-down of AINS have been discussed in several papers (see, for example, Prokhorov et al. 2002 and references therein). The general conclusion is that AINS should finally reach very long spin periods, mainly determined by the properties of turbulence in ISM. In the model of settling accretion, these general conclusions do not change qualitatively. However, quantitatively they are modified in the sense that an AINS can spin-down faster due to more effective angular momentum transport in the convective envelope surrounding the NS magnetosphere. Therefore, long spin periods of AINS should be reached faster than, for example, in previous calculations by Prokhorov et al. (2002).

To see the physics of the spin-down, we apply the basic equation describing viscous torques applied to a rotating ball of size R immersed in a liquid with density ρ , characterized by the dynamical viscosity coefficient $\rho \nu_l l$ (see, for example, Landau & Lifshitz 1959). Here ν_l is a characteristic velocity and l is a characteristic scale that determine the viscosity. The ball spin evolution is then:

$$\frac{dI\omega}{dt} = -8\pi\rho\nu_l l R^3 \omega, \quad (8)$$

where I is the moment of inertia of the ball and ω is the spin frequency.

If we substitute the ball by a gravitating body surrounded by convective shell, the characteristic velocity should be $\nu_l \sim v_{\text{ff}}(R_A)$, and $l \sim R_A$. Then we obtain:

$$\frac{1}{\omega} \frac{d\omega}{dt} = -8\pi\rho_{\infty} R_B^{3/2} \sqrt{2GM} R_A^2 I^{-1}. \quad (9)$$

This formula corresponds to an exponential spin-down with the characteristic spin-down time:

$$\tau_{\text{sd}} = I \left[8\pi\rho_{\infty} R_B^{3/2} R_A^2 \sqrt{2GM} \right]^{-1}. \quad (10)$$

Applying this formula to an AINS, we find that the spin-down time scale is:

$$\tau_{\text{sd}} = 7.6 \times 10^5 I_{45} v_7^3 \left(\frac{M}{1.5 M_{\odot}} \right)^{-2} \times \rho_{-24}^{-1} \mu_{30}^{-32/27} \left(\frac{L_x}{10^{27} \text{ erg s}^{-1}} \right)^{4/9} \text{ yrs}. \quad (11)$$

According to Eq.(9) AINS can reach very long (quasi) equilibrium periods (when the AINS spin is determined by the balance with turbulence in ISM, convection in the envelope, etc.) much faster than it was discussed by Prokhorov et al. (2002). These authors numerically calculated the spin evolution of a NS in ISM, and obtained that after starting accreting at spin periods about hundreds of seconds, the NS reaches a critical period of about few hours, when its behaviour starts to be significantly influenced by ISM turbulence, in $\sim 6 \times 10^7 \text{ yrs}$. Note also that Prokhorov et al. (2002) considered the model with linear decrease of the spin frequency, and in the situation we discuss here the spin-down is exponential.

4 DISCUSSION

The above considerations suggest that the settling accretion from ISM on to AINS naturally leads to low mean accretion luminosities $\dot{M}_x \ll \dot{M}_B$, in line with the lack of AINS detection so far. It does not look promising to hope for their detection in the near future as well, since the planned X-ray sensitivity, for example, of the SRG/eROSITA mission is expected to be $\sim 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ (Predehl et al. 2010). Then the expected X-ray luminosity of AINS $L_x \sim 10^{27} \text{ erg s}^{-1}$ suggests a limiting distance of 30 pc. According to Boldin & Popov (2010), only ~ 10 very dim candidates can be found in this volume, which are very difficult to identify.

However, the temporary enhancement of the accreting luminosity of AINS up to the Bondi value due to intrinsically intermittent character of accretion when the plasma cooling time much exceeds the free-fall time, as described above, may help detecting such sources. Additionally, the accreting gas can bring large magnetic field loops. Once captured into the accreting shell, the magnetic field will be enhanced close to the base of the shell near the magnetosphere. If the field in the loop is comparable with the magnetospheric field $B_m \sim B_0 (R_{\text{NS}}/R_A)^3$, the magnetic reconnection can happen. This would open the magnetospheric gates, and the entire shell around the NS can be accreted in a free-fall time from the Bondi radius. This mechanism was proposed by

Shakura et al. (2014) to explain the phenomenon of bright X-ray flares sporadically observed in an intensively studied subclass of high-mass X-ray binaries – supergiant fast X-ray transients (SFXTs) accreting from stellar winds of massive optical early-type companion. Apparently, the similar scenario can be applicable to the case of accretion from ISM on to INS.

AINS are expected to have much lower steady X-ray luminosities ($\lesssim 10^{30}$ erg s $^{-1}$, see Eq. 7) than SFXTs ($\sim 10^{34}$ erg s $^{-1}$) due to smaller settling radial velocities of matter in the shell (i.e. smaller factors $f(u)$). The smaller $f(u)$, the longer the matter stays in the boundary layer near the magnetosphere making it easier for reconnection to occur (see the discussion in Shakura et al. 2014). Once the magnetospheric gates are opened, plasma enters the magnetosphere with the free-fall velocity, and accretion proceeds at about the Bondi rate. Such a flare is expected to continue for about free-fall time from the Bondi radius:

$$t_{\text{ff}} = R_{\text{B}}/v(R_{\text{B}}) = 2GM/v^3 \approx 4 \times 10^5 v_7^{-3} \text{ s}. \quad (12)$$

Note that the X-ray luminosity during such a flare can be variable on the time scale $\sim R_{\text{A}}/v(R_{\text{A}}) \sim 100$ s for realistic conditions when $R_{\text{A}} \sim 10^{10}$ cm.

Therefore, during X-ray flares lasting for about from several hours to one day (when the entire shell is unstable) the X-ray luminosity from AINS can reach $L_{\text{x}} \sim 0.1 \dot{M}_{\text{B}} c^2 \sim 10^{31}$ erg s $^{-1}$. From a fiducial distance of 100 pc, this would correspond to an X-ray flux of $\sim 10^{-11}$ erg cm $^{-2}$ s $^{-1}$, well within the reach of the modern X-ray telescopes. It would be intriguing to search for such X-ray flares in the existing X-ray archives.

It is non-trivial to estimate the number of the potentially observable flares. We expect (see also Popov et al. 2000) that the spectrum from AINS would be thermal with typical temperatures $\lesssim 1$ keV. For such soft sources the operating Swift/BAT all-sky monitor is not very effective. The RXTE All-Sky Monitor (AMS) had a limiting sensitivity of ~ 20 mCrab, which corresponds to a minimum detectable flux of $\sim 4 \times 10^{-10}$ erg cm $^{-2}$ s $^{-1}$. If we neglect interstellar absorption (which may be well justified for small distances around 100 pc), then the limiting distance to AINS reduces to ~ 15 pc. With a local density of AINS of $\sim 10^{-4}$ pc $^{-3}$ (Boldin & Popov 2010) only a few sources can be found within this volume. The rate of possible flares short flares (with a duration of $t_{\text{inst}} \sim$ a few hours) can be rather high, but the rate of longer bursts caused by magnetic reconnection is difficult to estimate. The MAXI monitor onboard the International Space Station has observed the sky in the range 0.5–30 keV for 5 years. Potentially, its sensitivity for a one-day observation could be about a few mCrabs, however, detectors were gradually degrading, and the dimmest X-ray nova detected by this instrument have a peak flux of ~ 100 mCrab (see, for example, Mihara et al. 2014). With such a high flux threshold, again, we are left with a very small number of potentially observable sources. Additionally, the local ISM (inside ~ 100 pc) is dominated by the Local Bubble (see e.g. Posselt et al. 2008 for the discussion of a 3D model of the local ISM) filled with a hot low-density gas, and therefore the appearance of accreting isolated NSs can be greatly suppressed inside this volume. Probably, AINS (flaring or quasi-stationary) could be identified as serendipitous sources in the deep Chandra and XMM-Newton expo-

sure, but the analysis of this possibility is beyond the scope of this note.

5 CONCLUSIONS

In this short communication we discuss the observational signatures of isolated accreting NSs in the model of settling subsonic accretion, which is expected to naturally occur on to slowly rotating magnetized NS in ISM. It is shown that the average accretion luminosity of AINS should be significantly reduced relative to the Bondi accretion luminosity. Such NSs are expected to reach very long spin-periods in relatively short time $\lesssim 10^6$ yrs, after which their spin behaviour is mainly determined by the interstellar turbulence.

AINS can potentially be detected as transient X-ray sources due to the the intrinsically unstable character of settling accretion from magnetized ISM. The X-ray flares can last from hours up to about one day with a peak luminosity of $\sim 10^{31}$ erg s $^{-1}$, and can be searched for in the forthcoming X-ray survey mission like eROSITA. We stress that the presence of the characteristic time of order of one hour in the temporal X-ray variability can be a distinctive feature of AINS, which can be used to separate them from stellar flares that must show different time properties.

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REFERENCES

- Boldin P. A., Popov S. B., 2010, MNRAS , 407, 1090
- Bondi H., 1952, MNRAS , 112, 195
- Colpi M., Turolla R., Zane S., Treves A., 1998, ApJ , 501, 252
- Elsner R. F., Lamb F. K., 1977, ApJ , 215, 897
- Elsner R. F., Lamb F. K., 1984, ApJ , 278, 326
- Landau L. D., Lifshitz E. M., 1959, Fluid mechanics
- Langer S. H., Chanmugam C., Shaviv G., 1982, ApJ , 258, 289
- Mihara T., et al., 2014, ArXiv e-prints: 1410.6245
- Ostriker J. P., Rees M. J., Silk J., 1970, ApLett , 6, 179
- Popov S. B., Colpi M., Prokhorov M. E., Treves A., Turolla R., 2000, ApJL , 544, L53
- Popov S. B., Colpi M., Treves A., Turolla R., Lipunov V. M., Prokhorov M. E., 2000, ApJ , 530, 896
- Posselt B., Popov S. B., Haberl F., Trümper J., Turolla R., Neuhauser R., 2008, A&A , 482, 617
- Predehl P., et al., 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 7732 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, eROSITA on SRG. p. 0
- Predehl P., et al., 2011, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 8145 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, eROSITA. p. 0
- Prokhorov M. E., Popov S. B., Khoperskov A. V., 2002, A&A , 381, 1000

- Shakura N., Postnov K., Hjalmarsdotter L., 2013, MNRAS , 428, 670
- Shakura N., Postnov K., Kochetkova A., Hjalmarsdotter L., 2012, MNRAS , 420, 216
- Shakura N., Postnov K., Sidoli L., Paizis A., 2014, MNRAS , 442, 2325
- Shakura N. I., Postnov K. A., Kochetkova A. Y., Hjalmarsdotter L., 2013, Physics Uspekhi, 56, 321
- Shakura N. I., Postnov K. A., Kochetkova A. Y., Hjalmarsdotter L., Sidoli L., Paizis A., 2015, Astron. Rep. (in press, ArXiv e-prints: 1407.3163)
- Shvartsman V. F., 1971a, Soviet Astronomy, 15, 377
- Shvartsman V. G., 1971b, Soviet Astronomy, 14, 662
- Toropina O. D., Romanova M. M., Toropin Y. M., Lovelace R. V. E., 2003, ApJ , 593, 472
- Treves A., Colpi M., 1991, A&A , 241, 107
- Treves A., Turolla R., Zane S., Colpi M., 2000, PASP , 112, 297